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Electro Scientific Industries
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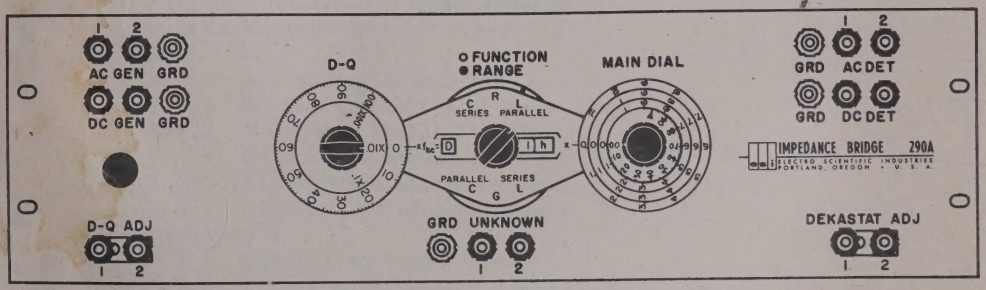
BRIDGES
AND
ACCESSORIES

JUNE 1966
REPLACES OCTOBER 1963

MODEL
290A

Instruction Manual

UNIVERSAL IMPEDANCE MEASURING SYSTEM



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6. CONVENIENT AUDIO FREQUENCY UNITS

7. PARTS LIST

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DEKAVIDER® Decade Voltage Divider
KELVIN KLIPS® Four-terminal Clips
KELVIN KLAMPS® Four-terminal Clamps
PORTAMETRIC® Portable Measuring Instrument
PVB® Potentiometric Voltmeter Bridge

1. INTRODUCTION

The ESI Model 290A Impedance Bridge combines a resistance, conductance, inductance, and capacitance bridge. Dissipation factor (D) and storage factor (Q) of inductors and capacitors are measured as part of the measurement of the primary characteristic.

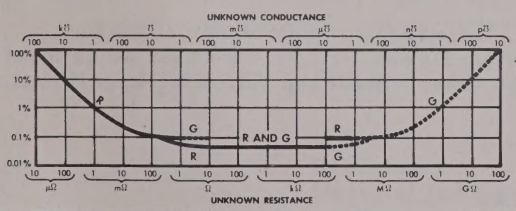
1.1 Specifications

The specified range and accuracy of the instrument are shown in the following table and graphs.

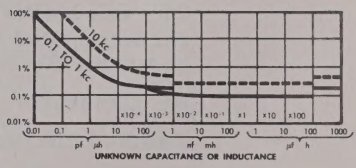
SELECTOR SWITCH SETTING	EQUIVALENT CIRCUIT	RANGES		ACCURACY △		
		MAGNITUDE	D or Q	L, R, C, G RANGE	MAGNITUDE	D or Q
R	R	0-1200 KILOHMS IN 7 RANGES;* 0.01 MILLIOHM PER DIAL DIV ON LOWEST R RANGE		HIGHEST	0.1% + 1 DIAL DIV	
				OTHER 5	0.05% + 1 DIAL DIV	
				LOWEST	0.1% + 1 DIAL DIV	
G	G	0-1200 MILLIMHOS IN 7 RANGES; 10 pmhos (100,000 MEGOHMS) PER DIAL DIVISION ON LOWEST G RANGE		HIGHEST	0.1% + 1 DIAL DIV	
				OTHER 5	0.05% + 1 DIAL DIV	
				LOWEST	0.1% + 1 DIAL DIV	
L Series	L_s Q	0-1200 HENRYS IN 7 RANGES; 0.01μh PER DIAL DIV ON LOWEST L RANGE	Q=0 TO 10.5 x f_{kc} IN 3 RANGES 0.001 x f_{kc} PER DIAL DIV ON LOWEST Q RANGE	HIGHEST	0.2% + 1 DIAL DIV + 1.2% x f_{kc}/Q	0.012 f_{kc} (i+Q^2) + 0.02Q
				OTHER 5	0.1% + 1 DIAL DIV + 0.7% x f_{kc}/Q	0.007 f_{kc} (i+Q^2) + 0.02Q
				LOWEST	0.2% + 1 DIAL DIV + 0.7% x f_{kc}/Q	0.007 f_{kc} (i+Q^2) + 0.02Q
L Parallel	L_p D	0-1200 HENRYS IN 7 RANGES; 0.01μh PER DIAL DIV ON LOWEST L RANGE	D=0 TO 10.5 x f_{kc} IN 3 RANGES 0.001 x f_{kc} PER DIAL DIV ON LOWEST D RANGE	HIGHEST	0.2% + 1 DIAL DIV + 1.2% x D x f_{kc}	0.012 f_{kc} (i+D^2) + 0.02D
				OTHER 5	0.1% + 1 DIAL DIV + 0.7% x D x f_{kc}	0.007 f_{kc} (i+D^2) + 0.02D
				LOWEST	0.2% + 1 DIAL DIV + 0.7% x D x f_{kc}	0.007 f_{kc} (i+D^2) + 0.02D
C Series	C_s D	0-1200 MICROFARADS IN 7 RANGES; 0.01pf PER DIAL DIV ON LOWEST C RANGE	D=0 TO 10.5 x f_{kc} IN 3 RANGES 0.001 x f_{kc} PER DIAL DIV ON LOWEST D RANGE	HIGHEST	0.2% + 1 DIAL DIV + 0.5% x D x f_{kc}	0.005 f_{kc} (i+D^2) + 0.02D
				OTHER 5	0.1% + 1 DIAL DIV + 0.5% x D x f_{kc}	0.005 f_{kc} (i+D^2) + 0.02D
				LOWEST	0.2% + 1 DIAL DIV + 1.0% x D x f_{kc}	0.010 f_{kc} (i+D^2) + 0.02D
C Parallel	C_p Q	0-1200 MICROFARADS IN 7 RANGES; 0.01pf PER DIAL DIV ON LOWEST C RANGE	Q=0 TO 10.5 x f_{kc} IN 3 RANGES 0.001 x f_{kc} PER DIAL DIV ON LOWEST Q RANGE	HIGHEST	0.2% + 1 DIAL DIV + 0.5% x f_{kc}/Q	0.005 f_{kc} (i+Q^2) + 0.02Q
				OTHER 5	0.1% + 1 DIAL DIV + 0.5% x f_{kc}/Q	0.005 f_{kc} (i+Q^2) + 0.02Q
				LOWEST	0.2% + 1 DIAL DIV + 1.0% x f_{kc}/Q	0.010 f_{kc} (i+Q^2) + 0.02Q

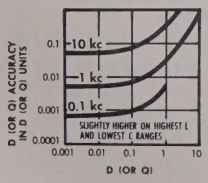
*Equivalent resistance measurements to 100,000 megohms are possible using the conductance ranges.

△ Accuracy specifications for inductors and capacitors apply for units with reasonably high Q (low D), at frequencies near 1 kc. The nominal frequency range is 100 cycles to 10 kc, with slight accuracy derating near the limits.

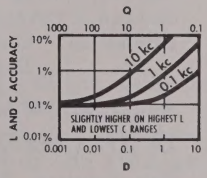


These curves show the specified accuracy for measurements of resistors and low loss inductors and capacitors.





The accuracy of inductance and capacitance measurements is influenced by the D or Q value. Graphs show the accuracy to be expected at various values of D or Q.



1.2 Accessories Required

1.2.1 For DC Measurements:

The ESI Models 800, 803, and 840 DC Generator-Detector or the 810 DC Detector and the 820 DC Generator are recommended for use with the Model 290A Bridge. If other dc generator and detector units are used, they should meet the following specifications:

DC Generator

Isolation: Resistance to ground must exceed 10 terohms, (10^{13} ohms).

Maximum Voltage: 400 volts open circuit.

Output Power: Limited to 1 watt or less

For example:

1.5 volts in series with 0.5 ohms or more
10 volts in series with 25 ohms or more
300 volts in series with 25 kilohms or more

1.2.2 DC Detector

Either a galvanometer or an electronic null detector can be used.

Electronic Null Detector:

Sensitivity: 10 microvolts per meter division

Noise: Less than 5 microvolts

Galvanometer:

Sensitivity: 0.03 microampere per meter division

Critical Damping: 2 kilohms or more

1.2.3 For AC Measurements:

The ESI Model 860A or 861A AC Generator and Detector unit are recommended for use with the Model 290A Bridge. If other ac generator and detector units are used, they should meet the following specifications:

AC Generator

Desired characteristics:

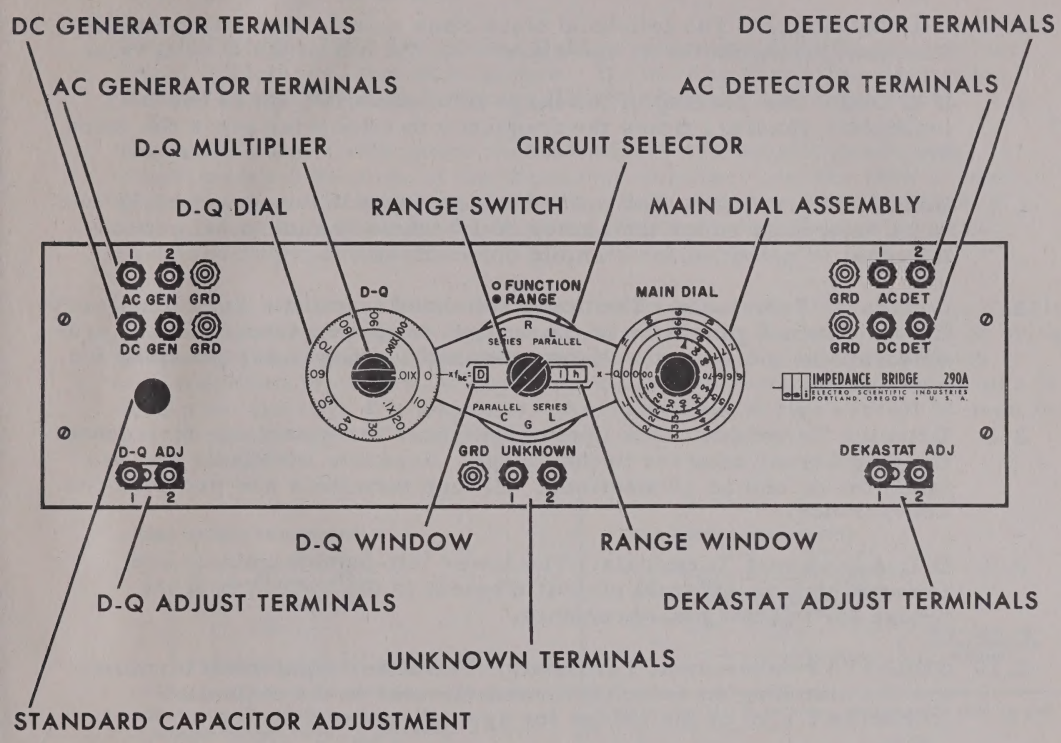
Frequency Range: 0.1 kc to 10 kc
Output Voltage: 0 to 20 volts open circuit
Series Protective Resistor: 100 ohms or more
Isolation: Capacitance of secondary to ground less than 30 pF
Direct capacitance secondary to primary less than 0.2 pF

AC Detector

Desired characteristics:

Sensitivity: 20 microvolts
Input Impedance: 500 kilohms
Harmonic Suppression: 30db by 2nd harmonic

2. CONTROLS



2.1 Circuit Selector: The large center dial selects the bridge circuit and connects the appropriate generator and detector.

Circuit		Measurement	Generator and Detector
1.	C_s	Series Capacitance	AC
2.	R^s	Resistance	DC
3.	L_p	Parallel Inductance	AC
4.	L^p_s	Series Inductance	AC
5.	G^s	Conductance	DC
6.	C_p	Parallel Capacitance	AC

The circuit in use is indicated by the mark at the edge of the selector switch. The electrical measurement unit is indicated in the right half of the right-hand window. For L or C measurements, the left-hand window shows whether the dissipation factor (D) or the storage factor (Q) is being measured.

2.2 Range Switch: The black center knob selects any of seven multipliers ranging from 10^{-4} to 100. The multiplier in use appears in the left half of the right-hand window.

2.3 Main Dial Assembly: The right-hand DEKASTAT dial reading times the range multiplier reading gives the value of resistance, conductance, inductance, or capacitance being measured.

2.4 D-Q Multiplier: The left-hand black knob selects the D-Q multiplier. The multiplying factor in use appears at the left of the D or Q value.

2.5 D-Q Dial: The reading of the large left-hand dial, times the D-Q multiplier reading, times the frequency in kilocycles gives the value of D or Q.

2.6 Unknown Terminals: The unknown component is connected to the two black terminals under the center dials. An adjacent metal ground terminal is provided for a shield connection.

2.7 Generator Terminals: The upper left-hand terminals are for connecting an external generator to the bridge. Separate terminals are provided for dc and ac connections. Ground terminals are provided for convenience.

2.8 Detector Terminals: The upper right-hand terminals are for connecting an external detector to the bridge. Separate terminals are provided for dc and ac connections. Ground terminals are provided for convenience.

2.9 D-Q Adjustment Terminals: The lower left-hand terminals are for attaching an external circuit element to the D-Q arm of the bridge for special measurements.

2.10 DEKASTAT Adjustment Terminals: The lower right-hand terminals are for attaching an external circuit element to the main dial DEKASTAT arm of the bridge for special measurements.

2.11 Standard Capacitor Adjustment: The left center hole cover conceals the adjusting screw for the standard capacitor. Setting this adjustment to give the correct bridge reading for an accurately known value of capacitance (0.1 μf recommended) assures a short term bridge accuracy rating improvement of 0.1% for all inductance and capacitance measurements.

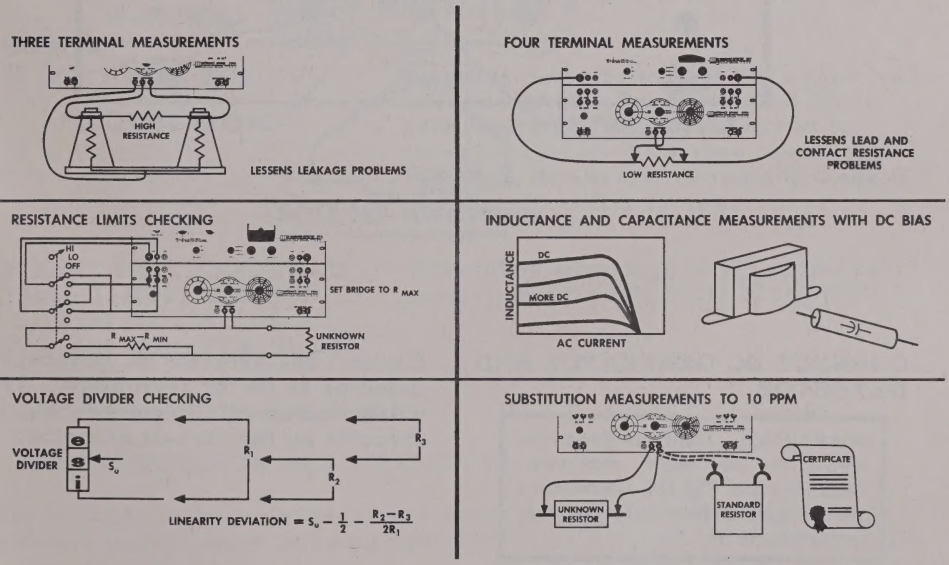
3. OPERATING INSTRUCTIONS

3.1 What the Bridge Measures

The ESI Model 290A Impedance Bridge measures resistance, conductance, inductance, and capacitance. It also measures the dissipation factor (D) and the storage factor (Q) of inductors and capacitors.

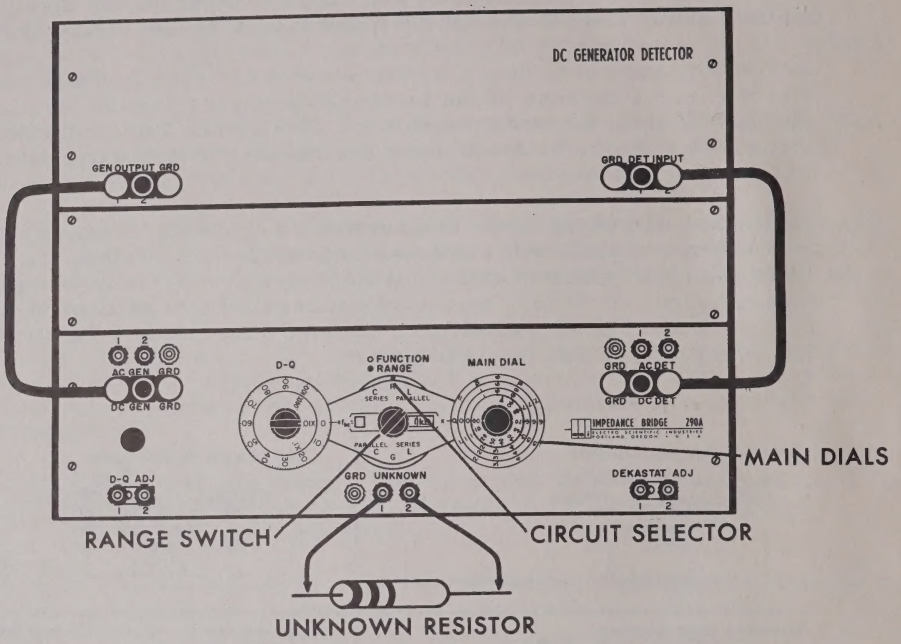
Resistance and conductance measurements are usually made with direct current because of the increased accuracy and the lack of hum pickup and stray capacitance effects. Resistance and conductance measurements can be made using ac, but they may require external reactance compensation.

Inductance and capacitance measurements are made in terms of a simple two-element circuit with the same impedance as the unknown. The bridge dials read the values of this equivalent circuit. To achieve highest measurement accuracy, an equivalent parallel circuit is used for high Q inductors and high D capacitors. An equivalent series circuit is used for low D capacitors and low Q inductors.



3.2 RESISTORS

3.2.1 MEASURING RESISTORS



CONNECT DC GENERATOR AND DETECTOR

Connect the external dc generator and detector to the dc terminals. They will be connected to the correct bridge circuits by the circuit selector.

> WARNING: Limit the generator output to one watt maximum. Recommended ESI DC Generators and Detectors have this protective feature built in.

CONNECT RESISTOR TO UNKNOWN TERMINALS

Make good contact with the terminals.

SET CIRCUIT SELECTOR TO R OR G

If between 0.83 ohm and 1.2 megohms, measure either RESISTANCE or CONDUCTANCE. If less than 0.83 ohm (>1.2 mho), measure RESISTANCE. If greater than 1.2 megohms (<0.83 micromho), measure CONDUCTANCE.

$$R \text{ in kilohms} = \frac{1}{G \text{ in millimhos}}$$

3.2.1 MEASURING RESISTORS (Cont.)

SET POWER SUPPLY VOLTAGE AND DETECTOR SENSITIVITY (See above WARNING)	Set the detector sensitivity so that the pointer is about half-way between the center and one end of the scale. Set the generator resistance to give the most detector deflection for any unbalance. Set the generator power for the maximum power that will not harm the device being tested. Recommended ESI generators are power-limited at one watt, and most have adjustable output power. See the instruction manual for the applicable generator for details on power adjustment.
SET MAIN DIAL TO READ 3.0000	This setting makes it easier to find the correct range.
SET RANGE SWITCH FOR MINIMUM DETECTOR SIGNAL	This sets the range so that the value can be found with maximum resolution on the main dial.
ADJUST MAIN DIAL FOR NULL	Increase detector sensitivity as the null is approached. Recommended ESI generators and detectors cannot be damaged by normal bridge use at any setting. Be careful to avoid damage if any other detector is used.
IF THE MAIN DIAL READING IS LESS THAN 1.2000, USE THE NEXT LOWER RANGE AND RE-ADJUST MAIN DIAL FOR NULL	This takes advantage of the increased resolution near full scale of the dial.

3.2.2 THINGS TO WATCH OUT FOR

3.2.2.1 HIGH RESISTANCE MEASUREMENTS

Care must be taken to avoid leakage resistance across the unit being measured. If an electronic null detector is being used it may be affected by ac hum picked up by the leads.

3.2.2.2 LOW RESISTANCE MEASUREMENTS

On the low resistance ranges the lead resistance in the unknown arm becomes significant. A correction for this resistance can be made as follows:

1. Short the test leads together at the point that they are to be connected to the unknown resistor and measure this "ZERO RESISTANCE".

2. Connect the test leads to the unknown resistor and measure the "RESISTANCE READING".

3. The "RESISTANCE VALUE" of the unknown resistor is then the "RESISTANCE READING" minus the "ZERO RESISTANCE".

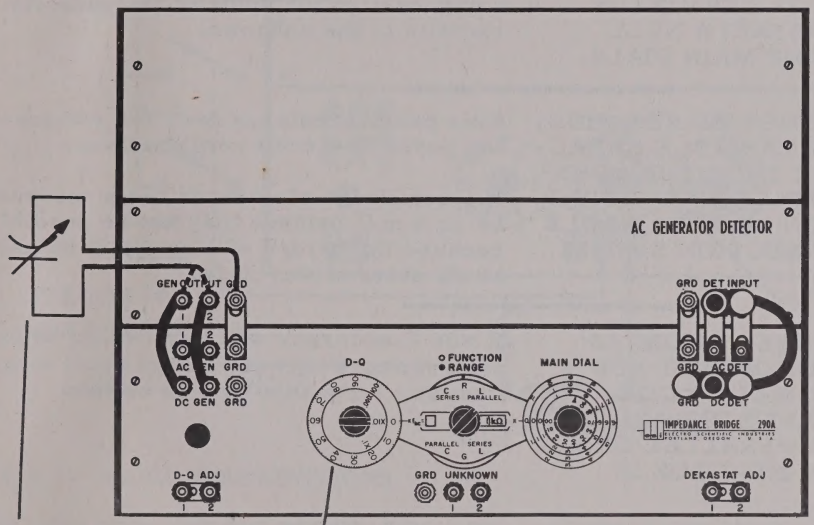
4. If the unknown resistance is to be connected directly to the terminals, the "ZERO RESISTANCE" reading can be taken by connecting a piece of heavy copper wire between the unknown resistance terminals. (#14 AWG copper wire has a resistance of about 0.00025 ohm/inch.)

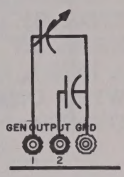
Sometimes thermal voltages are generated at connections and these can lead to erroneous balances of the bridge. If this condition is suspected, balance the bridge and then set the output switch to "reverse". If this results in a different galvanometer reading, change the main dial DEKASTAT® setting until the galvanometer reads the same for both output polarities. This cancels the effect of the thermal voltages.

3.2.3 MEASURING AC RESISTANCE

For greatest accuracy resistors should always be measured with dc. The accuracy of ac measurement will be 0.3% for one kilocycle and below over the range from one ohm to one megohm.

The indicated connections for the phase correction capacitor compensate for series inductance or parallel capacitance. It is impossible to seperate the correction for the unknown from that for the rest of the bridge circuit. If large reactances are involved the circuit should be measured as a capacitance or inductance and the resistance calculated.





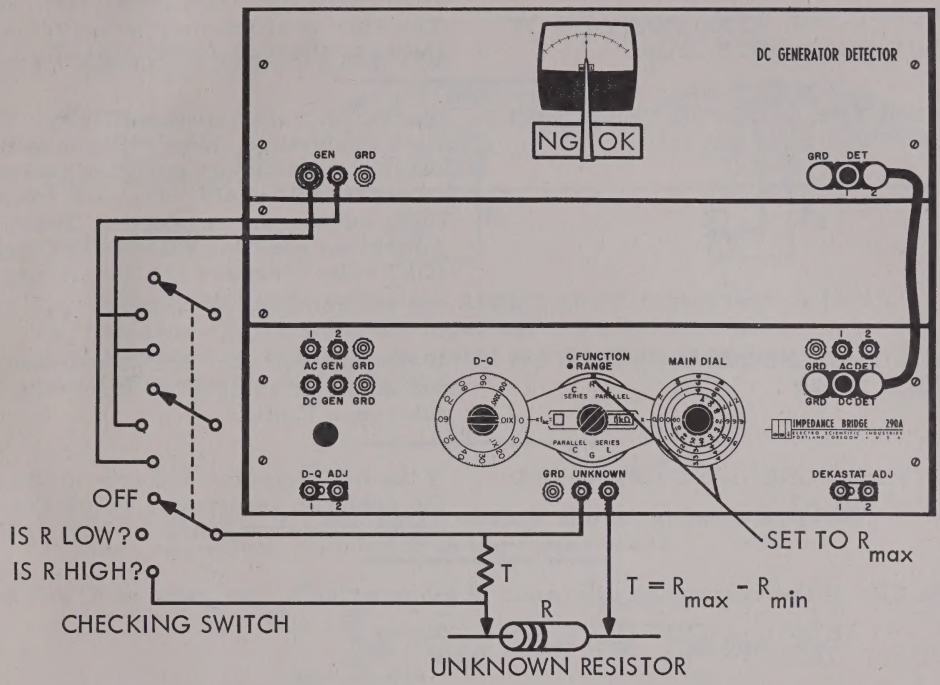
NOTE:
If the phase correction is small it may be convenient to connect a fixed capacitor to one terminal and a variable one to the other.

REMOVE THE AC GENERATOR CONNECTING STRAPS	The ac detector straps need not be removed
CONNECT THE BRIDGE DC GENERATOR AND DETECTOR TERMINALS TO THE AC GENERATOR AND DETECTOR	Short lengths of open-wire leads for the generator will minimize errors
SET THE BRIDGE ON THE R OR G RANGE	This connects the desired bridge circuit

TRY TO BALANCE THE BRIDGE AS WITH DC	Usually the eye will not completely open and/or the meter will not go completely to zero, thus indicating uncompensated phase shift
CONNECT A VARIABLE CAPACITOR FROM GROUND TO ONE OF THE GENERATOR TERMINALS AND TRY TO OBTAIN A NULL WITH IT AND THE MAIN DIALS.	Connecting the capacitor from ground to either generator terminal permits compensation for some of the possible circuits of the unknown.
IF A NULL CANNOT BE REACHED, CONNECT THE VARIABLE CAPACITOR BETWEEN THE OTHER GENERATOR TERMINAL AND GROUND. A NULL SHOULD BE OBTAINABLE WITH ONE CONNECTION OR THE OTHER.	This permits balance over the remaining possible circuit combinations. If a non linear element is being measured by ac a null balance may not be possible because the bridge will not be in balance at all parts of the cycle.
THE "RESISTANCE" VALUE AS READ WILL BE CORRECT FOR EQUIVALENT CIRCUITS CONSISTING OF A RESISTOR AND CAPACITOR IN PARALLEL OR A RESISTOR AND INDUCTOR IN SERIES.	R and G accuracy will be 0.3% or better for resistors between 1 ohm and 1 megohm at a frequency of 1 kc or less.

3.2.4 RESISTANCE LIMITS CHECKING

For rapidly checking resistance values between two tolerance limits.



3.2.4.1 BASIC INSTRUCTIONS

SET THE CIRCUIT SELECTOR TO R OR G. SET THE RANGE SWITCH AND MAIN DIAL DEKASTAT® TO THE UPPER RESISTANCE LIMIT.	These settings will allow checking both upper and lower limits.
CONNECT THE CIRCUIT AS SHOWN.	The generator reversal permits using the same direction of the null detector deflection for OK with both the upper and lower limit.
SHORT THE PROBES TOGETHER AND SHECK THE DIRECTION OF NULL DETECTOR DEFLECTION	The null detector should move to the right when the CHECKING SWITCH is in the IS R LOW? position. If it is not, reverse the polarity of the generator voltage or reverse the connections between the CHECKING SWITCH and the generator.
ATTACH THE PROBES TO THE UNKNOWN RESISTOR.	This completes the bridge circuit.

3.2.4.1 RESISTANCE LIMITS CHECKING (Cont.)

CHECK THE ZERO POSITION OF THE NULL DETECTOR.	The zero position may be adjusted by the null detector ZERO control.
FIND THE OPTIMUM SENSITIVITY SETTING BY TRIAL.	Start with minimum sensitivity. On the first resistance check, increase the detector sensitivity until the indication is nearly full scale. On each following test, reduce the sensitivity if the indication goes off scale to the right (OK) side; increase the sensitivity if the indication is close to zero.
SET THE CHECKING SWITCH TO "IS R LOW?".	If the null detector deflects to the right the unknown resistor is above the lower tolerance limit.
SET THE CHECKING SWITCH TO "IS R HIGH?".	If the null detector deflects to the right the unknown resistor is below the upper tolerance limit.

NOTE: If the resistance tolerance is given as $\pm\Delta\%$, the value of T will be $\frac{R2\Delta}{100}$ and R_{max} will be $\left(1 + \frac{\Delta}{100}\right) R$.

3.2.4.2 CHECKING HIGH RESISTANCE:

When checking high resistances, the voltage across the resistor will be high. The OFF position of the checking switch is provided to remove this voltage from the bridge while changing resistors.

3.2.4.3 CHECKING LOW RESISTANCE:

When checking low resistances the prove resistance R_o must be taken into account. It can be measured by shorting the probes. The bridge dials should be set to read $R_{max} + R_o$.

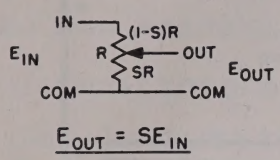
RESISTANCE LIMITS CHECKING

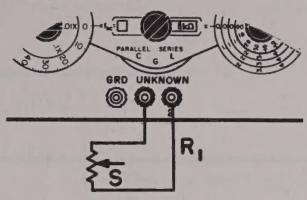
IF
$R_{MIN} < R < R_{MAX}$
AND IF
$T = R_{MAX} - R_{MIN}$
THEN
$(R_{MEAS}) < R_{MAX}$ Only if $R < R_{MAX}$
$(R_{MEAS} + T) > R_{MAX}$ Only if $R > R_{MIN}$

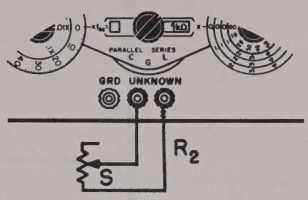
IF
$R(1+\Delta) = R_{MAX}$
$R(1-\Delta) = R_{MIN}$
THEN
$T = R2\Delta$

3.2.5 VOLTAGE DIVIDER CHECKING

3.2.5.1 SIMPLE TAPPED RESISTOR



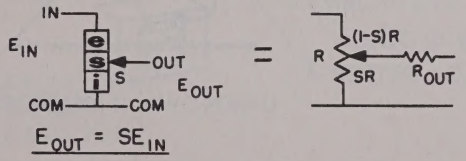


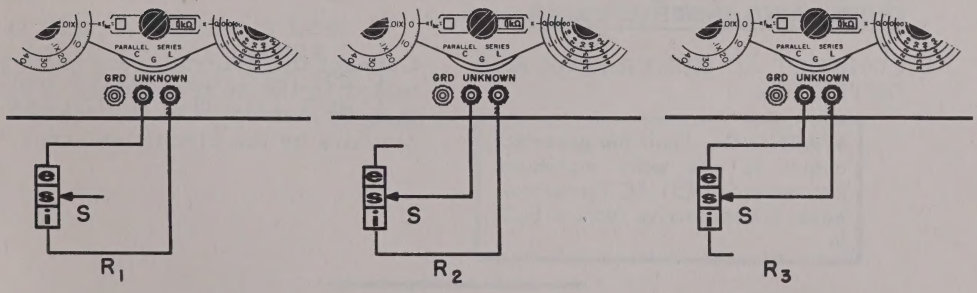


1. Follow the instructions for RESISTANCE measurement (3.2).
2. Measure R_1 between the input and common terminals.
3. Measure R_2 between the output and common terminals.
4. Calculate the divider setting S.

$$S = \frac{R_2}{R_1}$$

3.2.5.2 KELVIN VARLEY and other voltage divider types which may have equivalent resistance in the output lead.



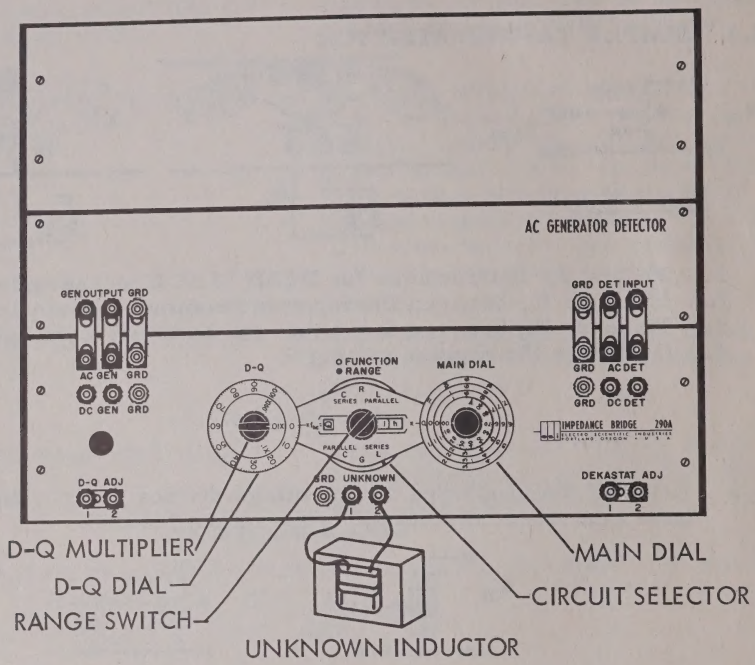


1. Follow the instructions for RESISTANCE measurement (3.2)
2. Measure R_1 between the input and common terminals.
3. Measure R_2 between the output and common terminals.
4. Measure R_3 between the input and output terminals.
5. Calculate the divider setting S.

$$S = \frac{1}{2} + \frac{R_2 - R_3}{2R_1}$$

3.3 INDUCTORS

3.3.1 MEASURING INDUCTORS



OPERATING INSTRUCTIONS

CONNECT AC GENERATOR AND DETECTOR

WARNING: Limit the generator output to one watt maximum. Recommended ESI AC Generators have this protective feature built in.

Connect the external generator and detector to the ac terminals. They will then be connected to the correct bridge circuits by the circuit selector.

CONNECT INDUCTOR TO UNKNOWN TERMINALS

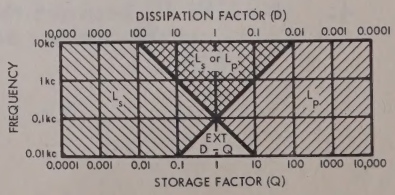
Make good contact with the terminals.

SET CIRCUIT SELECTOR TO L_p OR L_s

At 1 kc:

Use L_p for Q greater than 0.1

Use L_s for Q lower than 10



SET GENERATOR VOLTAGE AND DETECTOR GAIN

(See above WARNING)

SET MAIN DIAL TO READ 3.0000

SET D-Q MULTIPLIER TO .1x

SET D-Q DIAL TO:
0, IF BRIDGE MEASURES D,
OR 100, IF BRIDGE MEASURES Q

These settings make it easier to find the correct range.

SET RANGE SWITCH FOR MINIMUM DETECTOR SIGNAL

This sets the range so that the value can be found with maximum resolution on the main dial.

ADJUST MAIN DIAL AND D-Q DIAL ALTERNATELY FOR NULL

IF THE MAIN DIAL READING IS LESS THAN 1.2000, USE NEXT LOWER RANGE AND READJUST MAIN DIAL FOR NULL

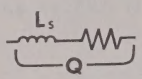
IF D-Q DIAL READING IS LESS THAN 10, USE NEXT LOWER SETTING OF D-Q MULTIPLIER AND READJUST D-Q DIAL FOR NULL

This takes advantage of the increased resolution near full scale of the dials.

3.3.2 SERIES AND PARALLEL INDUCTANCE

The bridge measures a simple equivalent circuit for the impedance connected to its terminals. This equivalent circuit consists of either an inductance and resistance connected in series or a different inductance and resistance connected in parallel. The phase and magnitude of the resulting impedance are identical for both circuits. For values of Q less than 100 the series and parallel inductances differ measurably (by more than 0.01%).

WHEN THE BRIDGE MEASURES SERIES INDUCTANCE, L_s:



L_s = (range switch setting) x (main dial reading)

Q = (D-Q multiplier setting) x (D-Q dial reading) x (f_{kc})

$D = \frac{1}{Q}$

$R_s = \frac{1}{Q} \times 2\pi f L_s$

$Z = 2\pi f L_s (\frac{1}{Q} + j)$

Q and D in per unit
R_s in kilohms
f in kc
L_s in henrys
$j = \sqrt{-1}$
Z in kilohms

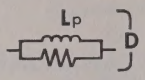
To calculate the equivalent parallel circuit:

The Q of the equivalent parallel circuit always equals the Q of the equivalent series circuit. The same is true of D.

$L_p = (1 + \frac{1}{Q^2}) \times L_s$

$R_p = Q \times 2\pi f L_p$

WHEN THE BRIDGE MEASURES PARALLEL INDUCTANCE, L_p:



L_p = (range switch setting) x (main dial reading)

D = (D-Q multiplier setting) x (D-Q dial reading) x (f_{kc})

$Q = \frac{1}{D}$

$R_p = \frac{1}{D} \times 2\pi f L_p$

$Z = \frac{2\pi f L_p (D+j)}{D^2 + 1}$

D and Q in per unit
R_p in kilohms
f in kc
L_p in henrys
$j = \sqrt{-1}$
Z in kilohms

To calculate the equivalent series circuit:

The D of the equivalent series circuit always equals the D of the equivalent parallel circuit. The same is true of Q.

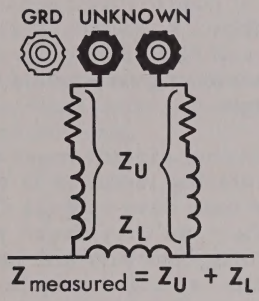
$L_s = \frac{1}{1 + D^2} \times L_p$

$R_s = D \times 2\pi f L_s$

3.3.3 THINGS TO WATCH OUT FOR

3.3.3.1 LOW INDUCTANCE MEASUREMENTS

The bridge measures the total impedance connected to its terminals. Both the unknown inductor and its leads contribute to this impedance. The leads have some resistance and inductance, which affect the value read from the bridge.



Z_U = Impedance of unknown inductor

Z_L = Impedance of leads

For greatest accuracy, minimize the lead impedance. Short heavy leads will reduce the resistance. Closely spaced twisted leads will reduce the inductance and the pickup of stray fields.

3.3.3.2 HIGH INDUCTANCE MEASUREMENTS

In making high inductance measurements, there are two things to watch out for:

1. Be careful to avoid hum pickup.
2. Keep the stray capacitance to a minimum.

To minimize both effects keep your hands as far as possible from the inductor measured.

Keep the leads as short and direct as possible. If extended leads are necessary, the lead from the center terminal should be shielded. See section 3.4.6 "Extended Leads".

Care should be taken to avoid coupling stray magnetic fields into the inductor being measured.

The D and Q readings on the highest L range will be in error as indicated in the specifications because of the residual capacitance of the range resistor. If accurate D or Q readings are needed the next lowest L range can be used. The L readings on the high range are accurate.

3.3.4 INDUCTANCE MEASUREMENTS WITH DC

3.3.4.1 WHEN TO USE DC

Iron core inductors are sensitive to both ac and dc current variations. Quantitative measurements of these effects can be made with the bridge.

3.3.4.2 THINGS TO WATCH OUT FOR

A. GENERAL PRECAUTIONS

Stray ac pickup may change sensitive components being measured or may give erroneous null detector readings.

The ac impedance of the dc external circuit must be greater than 2000 ohms for maximum sensitivity. If an isolating inductor is used to raise the ac impedance it may pick up stray signals or may have mutual coupling with the unknown inductor being measured. Either one may cause reading errors. Such an inductor should be well shielded magnetically and be placed to minimize its chance of interfering. For low currents isolation may be accomplished with a resistor instead of the inductor.

The parallel inductance circuit is recommended because it simplifies dc current measuring and bridge protection problems. With the series circuit the dc current divides between the bridge arms so that it is difficult to meter. The series circuit would also require a more careful analysis to avoid excessive current in any of the bridge arms.

If equivalent series inductance is required it can be easily calculated from the parallel inductance and D (See Sec. 3.3.2).

If D is too high to be read directly, an external rheostat such as the ESI Model DB 655 DEKASTAT®, connected to the D-Q ADJ terminals can be used to extend the D range. D can be calculated by the equation:

$$D = D_{reading} + 0.628\, R_{k\Omega}\, f_{kc}$$

where:

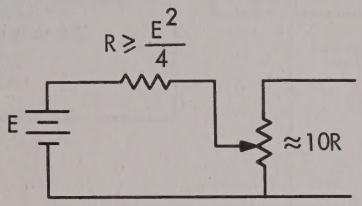
D	-	Dissipation factor of unknown
$D_{reading}$	-	Bridge D reading
R	-	External rheostat resistance in kilohms
f_{kc}	-	Operating frequency in kilocycles

B. WITH DC SUPPLIED THROUGH THE GENERATOR TERMINALS

Supplying the dc signal through the generator terminals allows more current for measuring inductors below 1.2 millihenrys. With this connection the dc current is not affected by balancing the bridge. A grounded dc generator cannot be used

because one of the detector terminals is grounded. Leakage capacitance and resistance from the dc source to ground will be across bridge arms and may cause significant errors.

If accuracy better than 0.1% is not required, the recommended ESI dc generators can be used in this application. They can be used without any additional equipment except an isolating capacitor, which is shown in the accompanying connection diagrams. If higher accuracy is required, a power-limited battery circuit that is well insulated from ground and has less than 10 pF capacitance to ground is recommended. The following circuit illustrates a power-limited variable circuit that has a maximum output power of 1 watt which will not damage the bridge under any conditions.



With the parallel inductance circuit the standard capacitor blocks the dc from all of the bridge arms except the inductor being measured and the range resistor. As a result the maximum allowable current will be limited by the range resistor. This current limit is shown in Section 3.3.4.3.

C. WITH DC SUPPLIED THROUGH THE DETECTOR TERMINALS

Supplying the dc signal through the detector terminals allows the use of higher current in measuring inductors above 1.2 millihenrys but the dc current will be influenced by the main dial DEKASTAT setting.

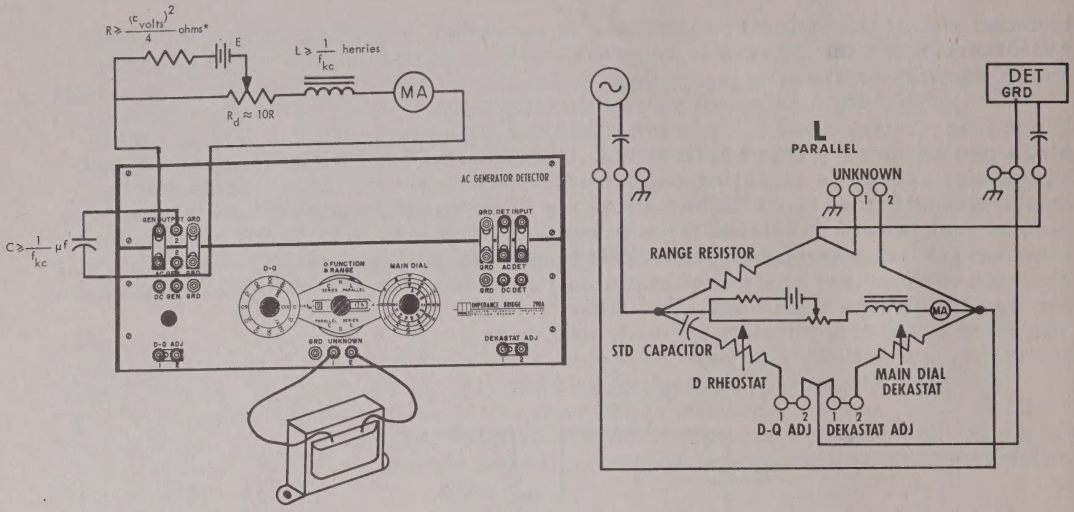
Since one of the detector terminals is normally grounded in recommended ESI detectors, a grounded power supply can be used.

The problems resulting from stray ac pickup either from the ripple of a dc supply, capacitive coupling to power lines or the bridge generator, stray field pickup by the isolating inductor (if used), or inductive coupling to the unknown inductor, are much more serious with this connection because of the direct coupling to the detector.

In this circuit the current goes through the unknown inductor and the main dial DEKASTAT. It must be limited by the values given in Section 3.3.4.4. If more current is needed the range can be increased by one setting and the first DEKASTAT dial turned to zero. This will decrease the DEKASTAT resistance and increase its current rating. Because of the high resolution of the main dial DEKASTAT accurate measurements are possible even when the first dial is not used. By setting the first two dials to zero higher current is possible but only 100 divisions of resolution are left.

3.3.4 INDUCTANCE MEASUREMENT WITH DC (cont'd.)

3.3.4.3 For parallel inductance measurement with dc superimposed through the generator terminals.



CONNECT AS SHOWN

E - VOLTAGE SOURCE	The detector input should have an isolating capacitor. This capacitor is built into the recommended ESI Detectors.
R - POWER LIMITING RESISTOR	Protects the bridge, detector and unknown inductor.
L - ISOLATING INDUCTOR	Avoid ac pickup and coupling to the unknown. Prevents excessive generator loading. Not necessary if R ⩾ 100 ohms.
C - ISOLATING CAPACITOR	Keeps dc out of the Generator.
R_d - CURRENT ADJUSTING CONTROL	To set desired current.
MA - CURRENT MONITORING METER	To measure dc current.

ADJUST THE DC CURRENT AS REQUIRED

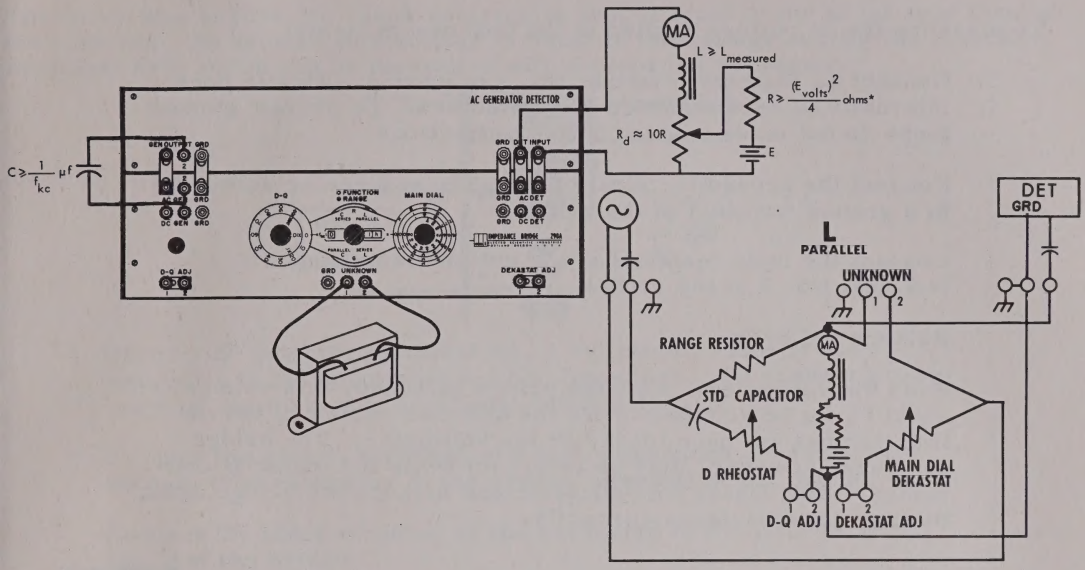
MEASURE THE INDUCTANCE — See Section 3.3

*This limits to one watt the dc power which can be supplied to the bridge thus protecting all of the bridge circuit. With care more current and voltage can be applied. The current rating of the bridge is given in the table below. These values should never be exceeded.

RANGE	UNKNOWN INDUCTANCE	MAXIMUM CURRENT
10^{-4}	0.1 μh to 1.2 mh	710 ma
10^{-3}	1 μh to 12 mh	230 ma
10^{-2}	10 μh to 120 mh	71 ma
10^{-1}	100 μh to 1.2 h	23 ma
1	1 mh to 12 h	7.1 ma
10	10 mh to 120 h	2.3 ma
100	100 mh to 1200 h	250 μa

3.3.4 INDUCTANCE MEASUREMENT WITH DC (cont'd.)

3.3.4.4 For parallel inductance measurements with dc superimposed through the detector terminals.



CONNECT AS SHOWN

E	- VOLTAGE SOURCE	The detector input should have an isolating capacitor. This capacitor is built into the recommended ESI Detectors.
R	- POWER LIMITING RESISTOR	Protects bridge, detector and unknown inductor.
L	- ISOLATING INDUCTOR	Avoid ac pickup and coupling to the unknown. Prevents excessive generator loading. Not necessary if $R \geq (L_{h\text{-measured}})\ (f_{kc})\ (6)$ kilohms.
C	- ISOLATING CAPACITOR	Keeps dc out of the Generator
R_d	- CURRENT ADJUSTING CONTROL	To set desired current.
MA	- CURRENT MONITORING METER	To measure dc current.

ADJUST THE DC CURRENT AS REQUIRED — The current will vary with the setting of the main dial.

MEASURE THE INDUCTANCE — See Section 3.3

*This limits to one watt the dc power which can be supplied to the bridge thus protecting all of the bridge circuit. With care more current and voltage can be applied. The current ratting of the bridge is given in the table below. The outer dial must be set to zero to use the "2nd" dial rating. Both outer dials must be set to zero to use the "3rd" dial rating. All three decades must be set to zero to use the rheostat rating. These values should never be exceeded.

RESOLUTION	DIAL	UNKNOWN INDUCTANCE**	MAXIMUM CURRENT
120,000 div	OUTER	100.0 μh to 1200 h	23 ma
10,000 div	2nd	10.0 μh to 100 h	71 ma
1,000 div	3rd	1.0 μh to 10 h	230 ma
105 div	RHEOSTAT	0.01 μh to 1.05 h	230 ma

**Lower limit is one division on dial which limits current on lowest range.

3.3.5 AC VOLTAGE MEASUREMENT

To measure the ac voltage applied to the unknown inductor:

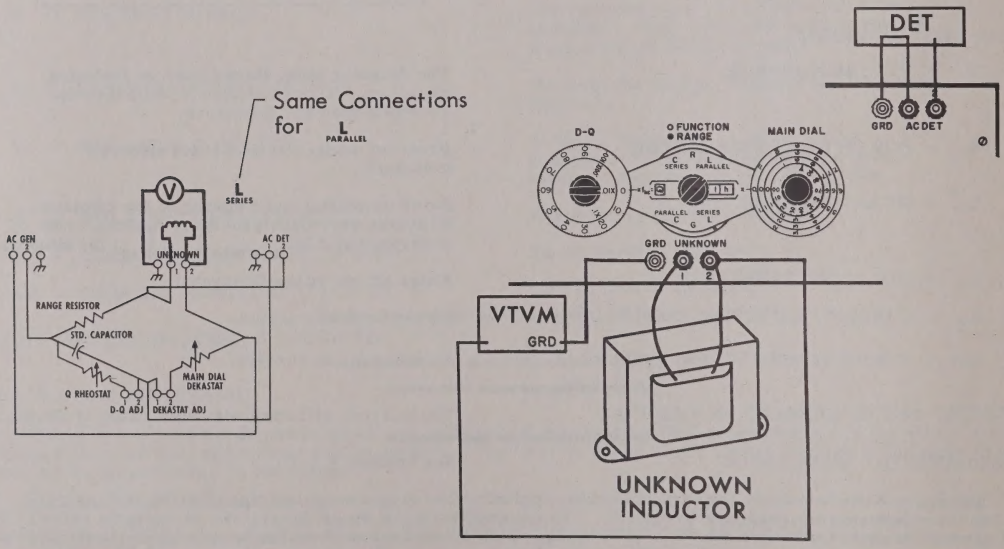
Connect ac detector terminal No. 1 to ground. This is done internally in recommended ESI Detectors. To prevent ground loops do not make any assitional connections.

Connect the ground terminal of a high impedance ac voltmeter to a ground terminal of the bridge.

Connect the input terminal of the voltmeter to unknown terminal No. 2 of the bridge.

Balance the bridge.

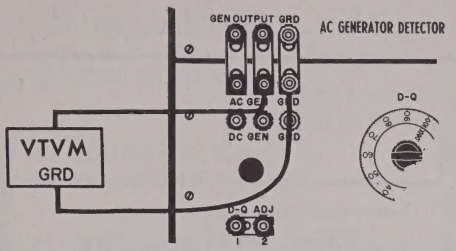
Read the voltmeter. With the bridge balanced, this voltage is equal to the ac voltage across the unknown inductor, but the inductor has not been loaded by the voltmeter. The bridge readings, however, may be incorrect while the meter is connected. Disconnect the voltmeter and balance the bridge again to measure inductance correctly.



3.3.6 AC CURRENT MEASUREMENT

To measure the ac current supplied to the unknown inductor:

The ac voltage across the range resistor is proportional to the ac current through the unknown. At balance this voltage is equal to the voltage across the standard capacitor arm which can be measured with a grounded voltmeter.



Connect ac detector terminal No. 1 to ground. This is done internally in the recommended ESI Detectors. To prevent ground loops do not make any additional connections.

Connect the ground terminal of a high impedance sensitive ac vacuum tube voltmeter to the ground terminal of the bridge.

Connect the input terminal of the voltmeter to AC GEN terminal No. 2 of the bridge.

Balance the bridge using either the series or parallel inductance circuit.

Read the voltmeter. The ac current in milliamperes will be equal to the voltage read (in volts) times the multiplier M from the following table.

$$I = V \times M$$

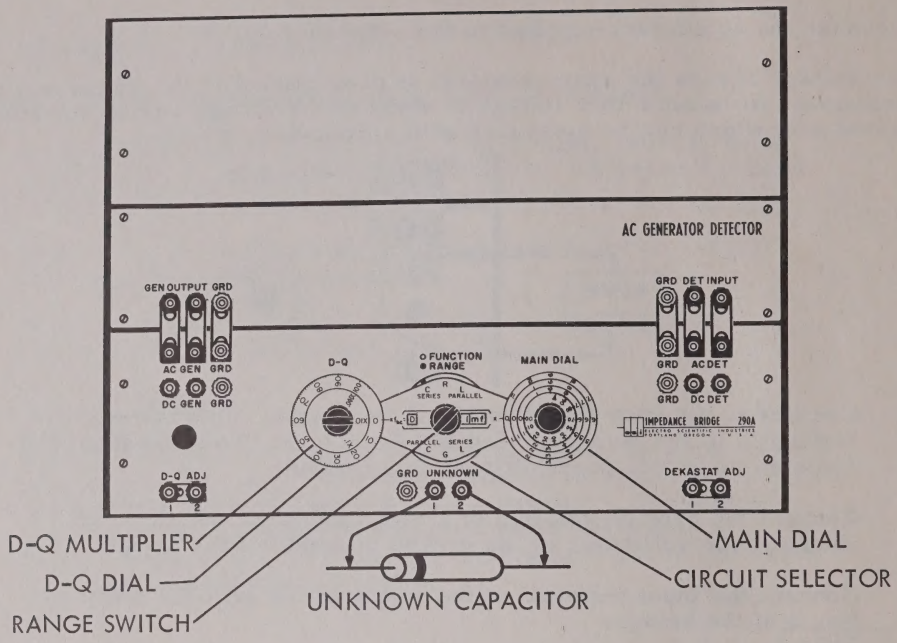
I - current in milliamperes
V - voltmeter reading in volts
M - multiplier from table

RANGE	UNKNOWN INDUCTANCE	M
10^{-4}	0.1 μh to 1.2 mh	1000
10^{-3}	1 μh to 12 mh	100
10^{-2}	10 μh to 120 mh	10
10^{-1}	100 μh to 1.2 h	1
1	1 mh to 12 h	0.1
10	10 mh to 120 h	0.01
100	100 mh to 1200 h	0.001

Remove the voltmeter and re-balance the bridge for the precise inductance measurement.

3.4 CAPACITORS

3.4.1 MEASURING CAPACITORS



OPERATING INSTRUCTIONS

CONNECT AC GENERATOR AND DETECTOR

Connect the external generator and detector to the ac terminals. They will then be connected to the correct bridge circuits by the circuit selector.

WARNING: Limit the generator output to one watt maximum. Recommended ESI AC Generators have this protective feature built in.

CONNECT CAPACITOR TO UNKNOWN TERMINALS

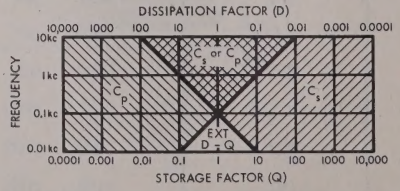
To minimize stray capacitance to ground, connect the outside foil to the left hand terminal.

SET THE CIRCUIT SELECTOR TO C_s OR C_p

At 1 kc:

Use C_p for D greater than 0.1

Use C_s for D lower than 10



Range of D and Q covered by C_s and C_p circuits.

SET GENERATOR VOLTAGE AND DETECTOR GAIN

(See Above WARNING)

SET MAIN DIAL TO READ 3.0000

SET D-Q MULTIPLIER TO .1x

SET D-Q DIAL TO
0, IF BRIDGE MEASURES D, OR
100, IF BRIDGE MEASURES Q

} These settings make it easier to find the correct range.

SET THE RANGE SWITCH FOR MINIMUM DETECTOR SIGNAL

This sets the range so that the value can be found with maximum resolution on the main dial.

ADJUST MAIN DIAL AND D-Q DIAL ALTERNATELY FOR NULL

IF THE MAIN DIAL READING IS LESS THAN 1.2000, USE NEXT LOWER RANGE AND READJUST MAIN DIAL FOR NULL

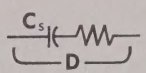
IF D-Q DIAL READING IS LESS THAN 10, USE NEXT LOWER SETTING OF D-Q MULTIPLIER AND READJUST D-Q DIAL FOR NULL

} This takes advantage of the increased resolution near full scale of the dials.

3.4.2 SERIES AND PARALLEL CAPACITANCE

The bridge measures a simple equivalent circuit for the impedance connected to its terminals. This equivalent circuit consists of either a capacitance and resistance connected in series or a different capacitance and resistance connected in parallel. The phase and magnitude of the resulting impedance are identical for both circuits. For values of D greater than 0.01 the series and parallel capacitances differ measurably (by more than 0.01%).

WHEN THE BRIDGE MEASURES SERIES CAPACITANCE, C_s:



C_s = (range switch setting) x (main dial reading)

D = (D-Q multiplier setting) x (D-Q dial reading) x (f_{kc})

$Q = \frac{1}{D}$

$R_s = \frac{D}{2\pi f C_s}$

$Z = \frac{D - j}{2\pi f C_s}$

D and Q in per unit
R_s in kilohms
f in kc
C_s in microfarads
$j = \sqrt{-1}$
Z in kilohms

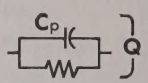
To calculate the equivalent parallel circuit:

The D of the equivalent parallel circuit always equals the D of the equivalent series circuit. The same is true of Q.

$C_p = \frac{C_s}{(1 + D^2)}$

$R_p = \frac{1}{D} \times \frac{1}{2\pi f C_p}$

WHEN THE BRIDGE MEASURES PARALLEL CAPACITANCE, C_p:



C_p = (range switch setting) x (main dial reading)

Q = (D-Q multiplier) x (D-Q dial reading) x (f_{kc})

$D = \frac{1}{Q}$

$R_p = \frac{Q}{2\pi f C_p}$

$Z = \frac{\frac{1}{Q} - j}{2\pi f C_p (1 + \frac{1}{Q^2})}$

Q and D in per unit
R_p in kilohms
f in kc
C_p in microfarads
$j = \sqrt{-1}$
Z in kilohms

To calculate the equivalent series circuit:

The Q of the equivalent series circuit always equals the Q of the equivalent parallel circuit. The same is true of D.

$C_s = (1 + \frac{1}{Q^2}) \times C_p$

$R_s = \frac{1}{Q} \times \frac{1}{2\pi f C_s}$

3.4.3 THINGS TO WATCH OUT FOR

3.4.3.1 LOW CAPACITANCE MEASUREMENTS

In making low capacitance measurements, there are two things to watch out for:

1. Be careful to avoid hum pickup.
2. Keep the stray capacitance to a minimum.

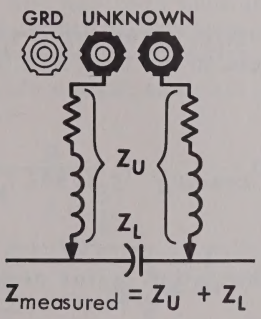
To minimize both effects, keep your hands as far as possible from the capacitor being measured.

Keep the leads as short and direct as possible. If extended leads are necessary, the lead from the center terminal should be shielded. See section 3.4.6, "Extended Leads".

The D and Q readings on the lowest C range will be in error as indicated in the specifications because of the residual capacitance of the range resistor. If accurate D or Q readings are needed the next highest C range can be used. The C readings on the low range are accurate.

3.4.3.2 HIGH CAPACITANCE MEASUREMENTS

The bridge measures the total impedance connected to its terminals. Both the unknown capacitor and its leads contribute to this impedance. The leads have some resistance and inductance, which affect the value read from the bridge.



Z_U = Impedance of unknown capacitor

Z_L = Impedance of leads

For the greatest accuracy, minimize the lead impedance. Short heavy leads will reduce the resistance. Closely spaced twisted leads will reduce the inductance and the pickup of stray fields.

3.4.4 CAPACITANCE MEASUREMENT WITH DC

3.4.4.1 WHEN TO USE DC

Some capacitors need a polarizing voltage. For example, electrolytic and tantalytic capacitors can be damaged by the reverse polarity half-cycle of the test frequency. Even if the capacitors are not damaged, erroneous readings may result.

A polarizing voltage is not always needed in these measurements. If the ac voltage is kept at a very low value (typically below one-half volt), the capacitor will not be damaged, and the readings will be reasonably accurate.

3.4.4.2 THINGS TO WATCH OUT FOR

Stray ac pickup may change sensitive components being measured or may give erroneous null detector readings.

The ac impedance of the external dc circuit must be less than 200 ohms for maximum sensitivity.

The series capacitance circuit is recommended because it simplifies dc voltage protection and measuring problems. With the parallel circuit the dc voltage divides between the bridge arms so that it is difficult to meter. This also requires a more careful analysis to avoid excessive voltage across any of the bridge arms.

If equivalent parallel capacitance is required it can be easily calculated from the series capacitance and D. See section 3.4.2.

If D is too high to be read directly, an external rheostat such as the ESI Model DB 655 DEKASTAT®, connected to the D-Q ADJ terminals can be used to extend the D range. If the series capacitance circuit is used, D can be calculated by the equation:

$$D = D_{reading} + \frac{R}{1.592\, f_{kc}}$$

where:

D	-	Dissipation factor of unknown capacitor
$D_{reading}$	-	D Reading of bridge
R	-	External rheostat resistance in kilohms
f_{kc}	-	Operating frequency in kilocycles

3.4.4.2 THINGS TO WATCH OUT FOR (cont'd.)

If the equivalent series resistance of the capacitor being measured is much greater than the resistance of the range resistor most of the dc input voltage will appear across the unknown capacitor. If the dc resistance of the unknown capacitor is known the voltage across it will be shown by the following equation:

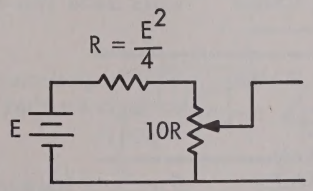
$$E_c = E_{in} \frac{R_c}{R_c + R_R}$$

where:

E_c - DC voltage across the unknown capacitor
E_{in} - DC voltage at the generator terminals
R_c - DC resistance of the unknown capacitor
R_R - Resistance of the range resistor

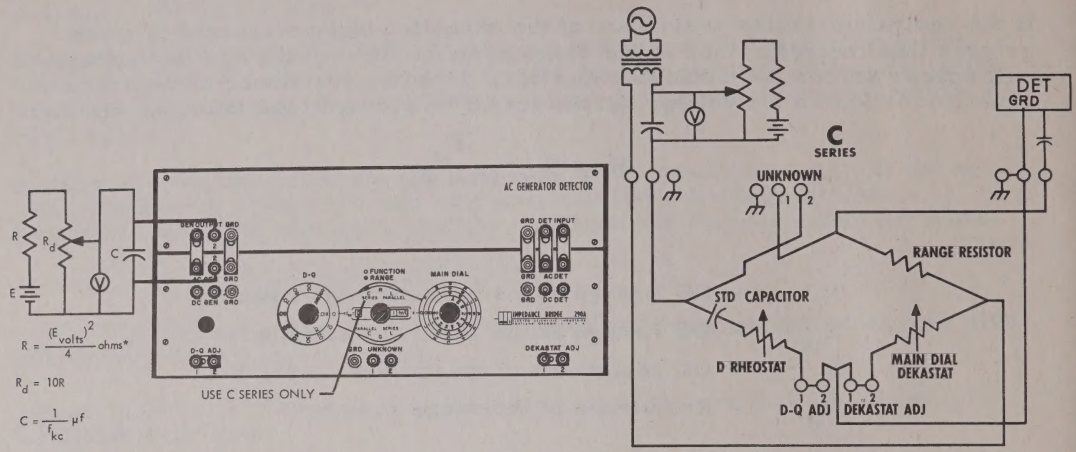
A grounded dc generator cannot be used because one of the detector terminals is grounded. Leakage capacitance and resistance from the dc source to ground will be across bridge arms and may cause significant errors.

If accuracy better than 0.1% is not required, the recommended ESI dc generators can be used in this application. They can be used without any additional equipment except an isolating capacitor, which is shown in the accompanying connection diagrams. If higher accuracy is required, a power-limited battery circuit that is well insulated from ground and has less than 10 pF capacitance to ground is recommended. The following circuit illustrates a power-limited variable circuit that has a maximum output power of 1 watt which will not damage the bridge under any conditions.



With the series inductance circuit the standard capacitor is subjected to the same dc voltage as the unknown capacitor. As a result the maximum allowable voltage must be limited to the standard capacitor rating of 300 volts.

3.4.4.3 FOR SERIES CAPACITANCE MEASUREMENTS WITH SUPERIMPOSED DC:



CONNECT THE CIRCUIT AS SHOWN	The detector input should have an isolating capacitor. This capacitor is built into recommended ESI Detectors.
E - DC VOLTAGE SOURCE	Battery recommended to avoid stray pickup and leakage
R - POWER LIMITING RESISTOR $R = \frac{(E_{volts})^2}{4}$ ohms*	This protects the bridge in case the unknown terminals are shorted.
R_D - VOLTAGE ADJUSTING CONTROL	This sets the dc voltage.
CONNECT THE METER "V" IN PARALLEL WITH THE DC SUPPLY	The impedance of most meters is high enough so that they will not load the dc supply.
ADJUST THE DC VOLTAGE AS REQUIRED	For low leakage capacitors the voltage across the unknown capacitor will be equal to the voltmeter "V" reading.
MEASURE THE CAPACITANCE	See section 3.3.4.

*This limits the dc power that can be supplied to the bridge to one watt to protect all of the bridge circuit in case the unknown capacitor is accidentally shorted. The maximum dc supply should not exceed 300 volts for the protection of the standard capacitor.

3.4.5 AC VOLTAGE MEASUREMENT

To measure the ac voltage applied to the unknown capacitor:

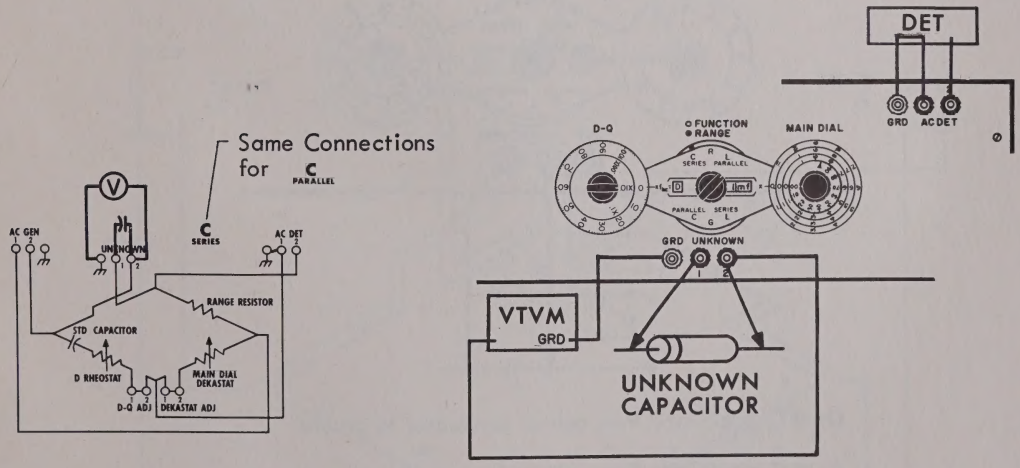
Connect ac detector terminal No. 1 to ground. This is done internally in recommended ESI Detectors. To prevent ground loops do not make any additional connections.

Connect the ground terminal of a high impedance ac voltmeter to the ground terminal of the bridge.

Connect the input terminal of the voltmeter to unknown terminal No. 2 of the bridge.

Balance the bridge.

Read the voltmeter. With the bridge balanced, this voltage is equal to the ac voltage across the unknown capacitor, but the capacitor has not been loaded by the voltmeter. The bridge readings, however, may be incorrect while the meter is connected. For the correct capacitance reading, disconnect the voltmeter from terminal No. 2 and rebalance the bridge.



3.4.6 EXTENDED LEADS

Sometimes it is necessary to use extended leads. This can be done easily without causing error in the measurement.

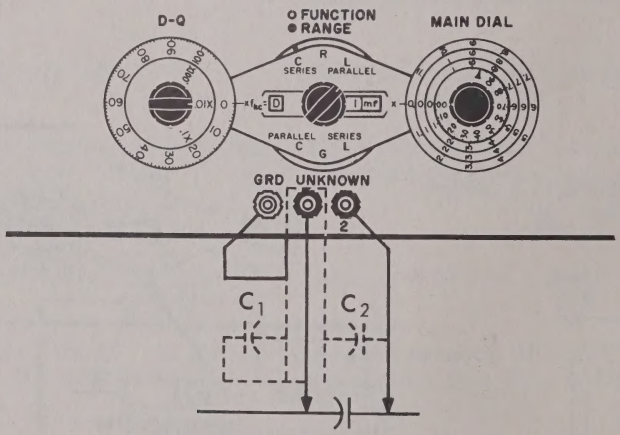
Connect a shielded lead to Unknown terminal No. 1.

Connect the shield of this lead to the adjacent GRD terminal of the bridge.

Connect an unshielded lead to Unknown terminal No. 2.

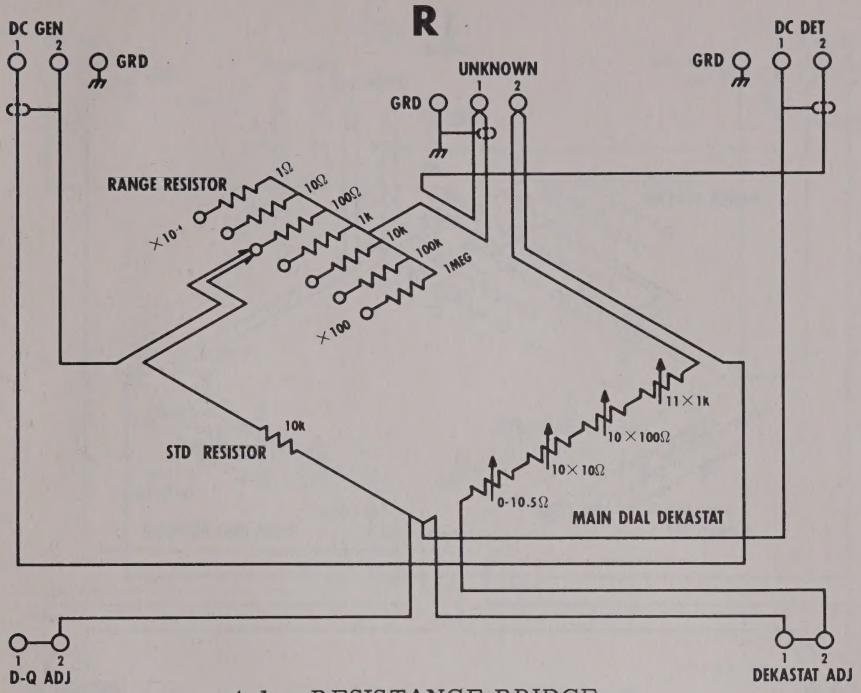
The capacitance between the shield and the center conductor is now across the detector. This keeps it from causing any error. If this stray capacitance is greater than 500 pF, it may reduce the detector sensitivity.

The stray capacitance from the unshielded lead to ground is across the standard capacitance arm of the bridge. As the standard capacitor is 100,000 pF, the stray capacitance will not cause significant errors unless it exceeds a few 10's of pF.

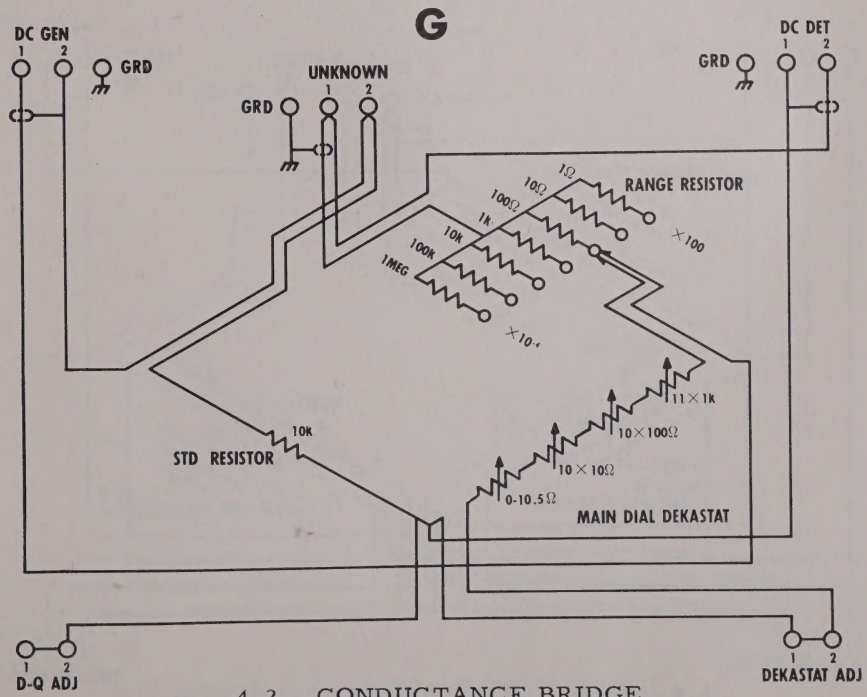


C_1 = Capacitance from center conductor to ground

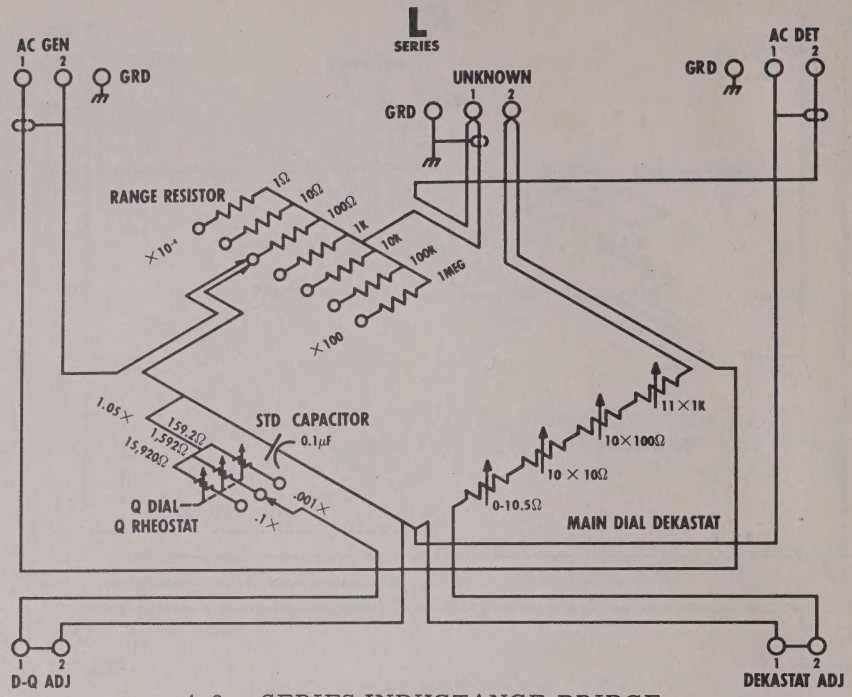
C_2 = Capacitance from unshielded conductor to ground



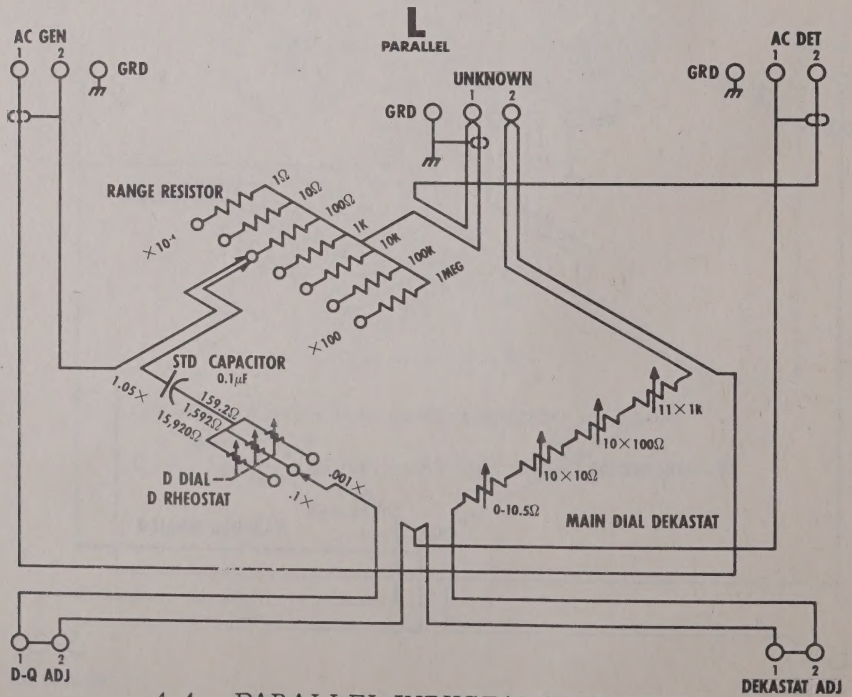
4.1 RESISTANCE BRIDGE



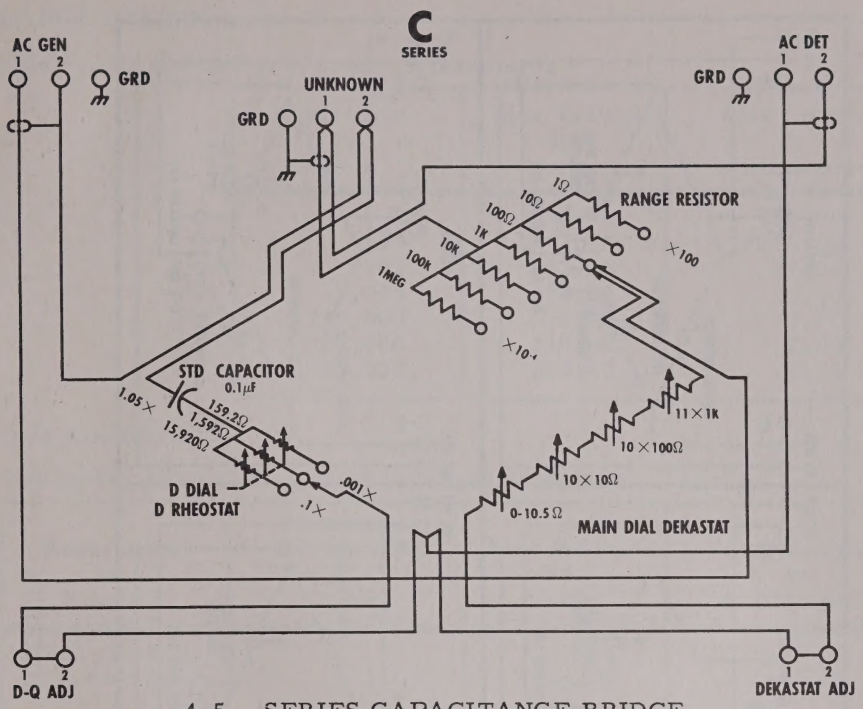
4.2 CONDUCTANCE BRIDGE



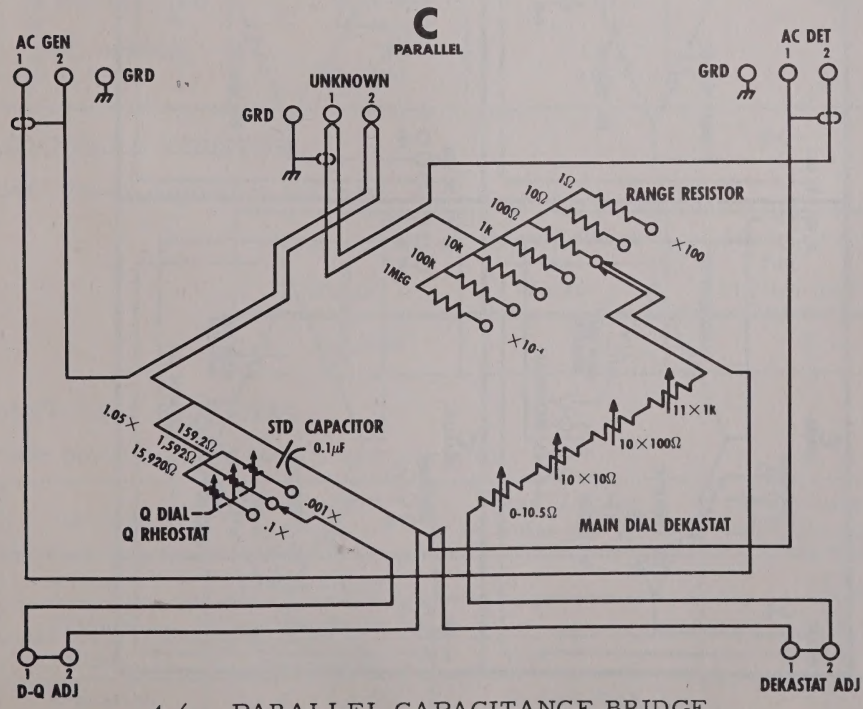
4.3 SERIES INDUCTANCE BRIDGE



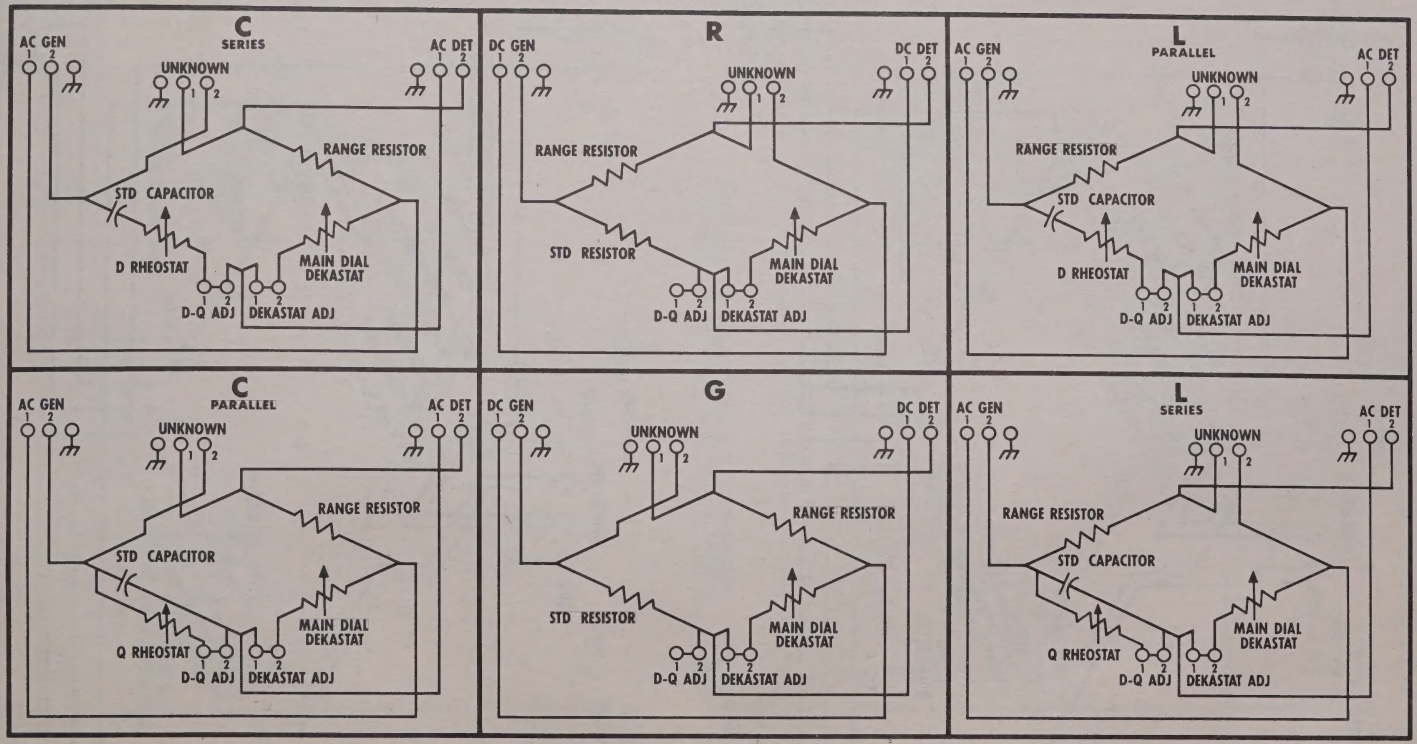
4.4 PARALLEL INDUCTANCE BRIDGE



4.5 SERIES CAPACITANCE BRIDGE



4.6 PARALLEL CAPACITANCE BRIDGE



4.7 BASIC CIRCUITS

5. BRIDGE ELEMENT VOLTAGE AND CURRENT LIMITS

RANGE RESISTORS

Safe Power limited to 1/2 watt per resistor

Resistance in Ohms	Max Voltage in Volts	Max Current in Milliamperes
1	0.71	710.00
10	2.30	230.00
100	7.10	71.00
1,000	23.00	23.00
10,000	71.00	7.10
100,000	230.00	2.30
1,000,000	250.00	0.25

D-Q RHEOSTATS

Safe power limited to 7 watts into total resistance

Resistance in Kilohms	Maximum Resistance in Ohms	Max Voltage in Volts	Max Current in Milliamperes
D-Q reading x 0.01592	166	35	210
D-Q reading x 0.1592	1,670	110	68
D-Q reading x 1.5920	16,750	350	21

STANDARD RESISTOR

Safe power limited to 1/2 watt

Resistance in Ohms	Max Voltage in Volts	Max Current in Milliamperes
10,000	71	7.1

MAIN DIAL RHEOSTAT

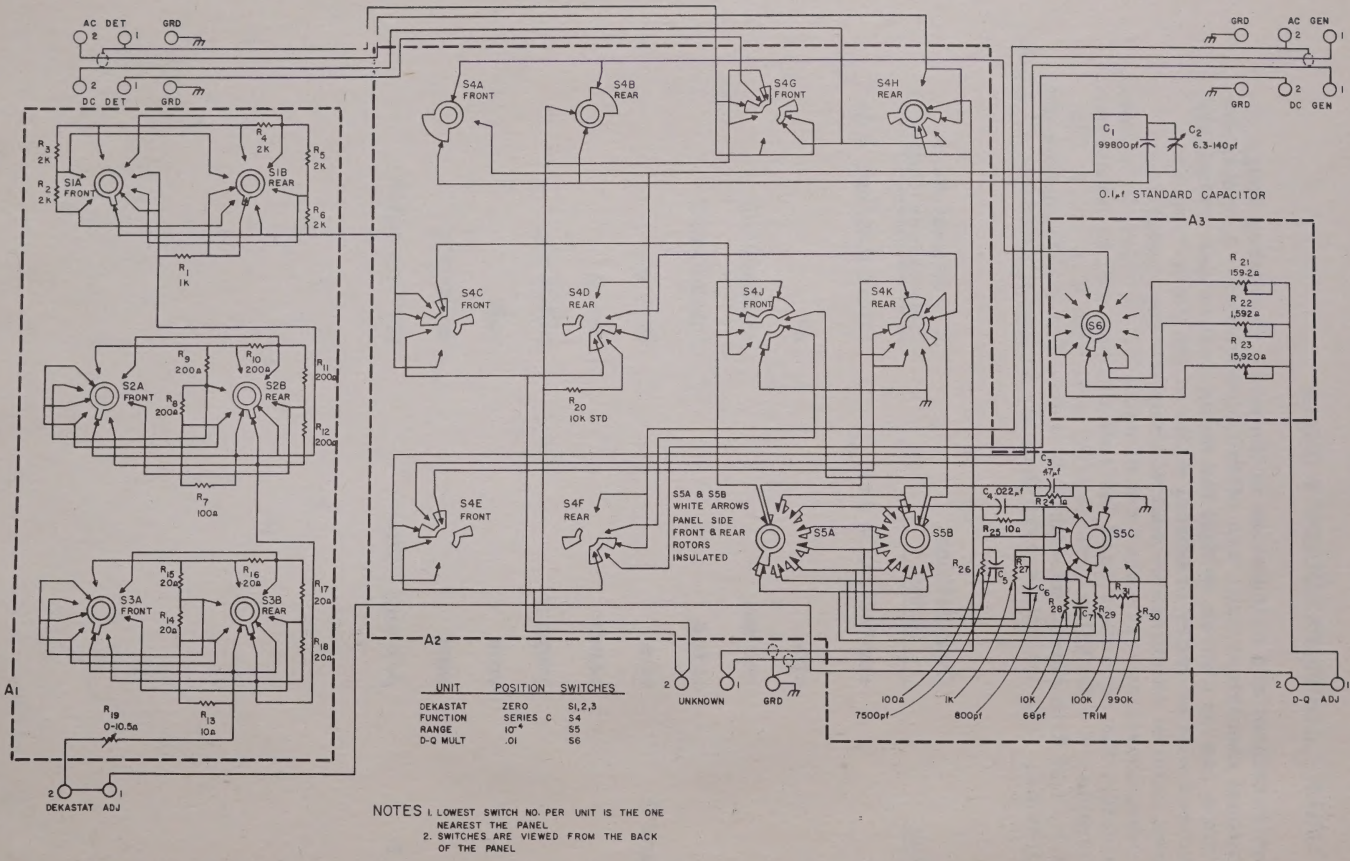
Safe power limited to 1/2 watt per step

Decade	Resistance in Ohms	Max Voltage in Volts per Step	Max Current in Milliamperes
First	1000Ω steps	23	23
Second	100Ω steps	7.1	71
Third	10Ω steps	2.3	230
Rheostat	0 - 10.5Ω	2.3 at max	230

6. CONVENIENT AUDIO FREQUENCY UNITS

For measurement and calculation in the audio frequency range the conventional electrical units are often inconvenient. A consistent set of units can be chosen so that the numerical values commonly encountered will be more practical while at the same time the equations used in calculations will not require any troublesome conversion constants. If either set of units listed below is followed consistently, the equations used for calculations will be unaltered. For example, E = IR holds true equally well with E in volts, I in amperes, and R in ohms; or with E in volts, I in milliamperes and R in kilohms. The 291 dials read directly in these "convenient" units.

Function	Conventional Units	Convenient Audio Frequency Units
ω	radian/sec = $2\pi f_{cps}$	kiloradian/sec = $2\pi f_{kc}$
f	cps	kc
t	second	millisecond
C	farad	microfarad
Z, R and X	ohm	kilohm
L	henry	henry
I	ampere	milliamp
E	volt	volt
P	watt	milliwatt
Q and D	per unit ratio	per unit ratio



NOTES
1. LOWEST SWITCH NO. PER UNIT IS THE ONE NEAREST THE PANEL
2. SWITCHES ARE VIEWED FROM THE BACK OF THE PANEL

MODEL 290A IMPEDANCE BRIDGE WIRING DIAGRAM

7. PARTS LIST

The following parts list is in alpha-numerical order of the circuit reference designator. Miscellaneous parts are included at the end of the list. Manufacturer of the part is given in a code number according to the Federal Supply Code for Manufacturers; see list of manufacturers below. Parts recommended as spares to sustain operation in isolated locations are indicated in the recommended spare parts column.

Parts manufactured by Electro Scientific Industries must be ordered from the factory. When ordering parts from the factory include the following information:

Model and serial number of the instrument
Electro Scientific Industries part number
Circuit reference designator
Description of part

CODE LIST OF MANUFACTURERS

11837	ELECTRO SCIENTIFIC INDUSTRIES Portland, Oregon
56289	SPRAGUE ELECTRIC CO. North Adams, Massachusetts
65092	WESTON INSTRUMENTS DIVISION OF DAYSTROM, INC. Newark, New Jersey
80583	HAMMARLUND CO., INC. New York, New York
84171	ARCO ELECTRONICS INC. Great Neck, New York

Ckt Ref	Description	Mfr	ESI Part No.	Qty Used	Recm SP
A_1	Ass'y, DEKASTAT	11837	3215	1	1
A_2	Ass'y, Multiplier Function	11837	3298	1	1

Ckt Ref	Description	Mfr	ESI Part No.	Qty Used	Recm SP
A_3	Ass'y, DQ Rheostat	11837	3211	1	1
C_1	Capacitor, Std 0.1μf	11837		1	1
C_2	Capacitor, variable, 6.3-140 pf Mfr PN APC-140-C	80583		1	
C_3	Capacitor, fixed, .47μf ±10%, Subminiature Metal Clad Mfr PN 178P479153, Part of Ass'y A_2	56289		1	
C_4	Capacitor, fixed, .022μf ±10%, Black Beauty Mfr PN 109P22342, Part of Ass'y A_2	56289		1	
C_5	Capacitor, fixed, 7500pf ±1%, mica, Mfr PN CM35E752F, Part of Ass'y A_2	84171		1	
C_6	Capacitor, fixed, 800pf ±5%, mica, Mfr PN CM20D8015, Part of Ass'y A_2	84171		1	
C_7	Capacitor, fixed, 68pf ±5%, mica, Mfr PN CM15E680J, Part of Ass'y A_2	84171		1	
R_1	Resistor, fixed, precision, 1k, Part of Ass'y A_1	11837	*	1	*
$R_{2,3,4,5,6}$	Resistor, fixed, precision, 2k, Part of Ass'y A_1	11837	*	5	*

* Replace entire ass'y

Ckt Ref	Description	Mfr	ESI Part No.	Qty Used	Recm SP
R_7	Resistor, fixed, precision, 100Ω, Part of Ass'y A_1	11837	*	1	*
$R_{8,9,10,11,12}$	Resistor, fixed, precision, 200Ω, Part of Ass'y A_1	11837	*	5	*
R_{13}	Resistor, fixed, precision, 10Ω, Part of Ass'y A_1	11837	*	1	*
$R_{14,15,16,17,18}$	Resistor, fixed, precision, 20Ω, Part of Ass'y A_1	11837	*	5	*
R_{19}	Resistor, variable, 10.5Ω, Part of Ass'y A_1	11837	*	1	*
R_{20}	Resistor, fixed, precision, 10k, Part of Ass'y A_2	11837	*	1	*
R_{21}	Resistor, variable, 159.2Ω, Part of Ass'y A_3	11837	*	1	*
R_{22}	Resistor, variable, 1592Ω, Part of Ass'y A_3	11837	*	1	*
R_{23}	Resistor, variable, 1592Ω, Part of Ass'y A_3	11837	*	1	*
R_{24}	Resistor, fixed, precision, 1Ω, Part of Ass'y A_2	11837	*	1	*
R_{25}	Resistor, fixed, precision, 10Ω, Part of Ass'y A_2	11837	*	1	*
R_{26}	Resistor, fixed, precision, 100Ω, Part of Ass'y A_2	11837	*	1	*

* Replace entire Ass'y

Ckt Ref	Description	Mfr	ESI Part No.	Qty Used	Recm SP
R_{27}	Resistor, fixed, precision, 1k, Part of Ass'y A_2	11837	*	1	*
R_{28}	Resistor, fixed, precision, 10k, Part of Ass'y A_2	11837	*	1	*
R_{29}	Resistor, fixed, precision, 100k, Part of Ass'y A_2	11837	*	1	*
R_{30}	Resistor, fixed, vamistor, 990k, Mfr PN 9852, Part of Ass'y A_2	65092		1	*
R_{31}	Resistor, fixed, sel. to adj R_{30}, Part of Ass'y A_2			1	*
$S_{1,2,3}$	Switch, Part of Ass'y A_1	11837	*	3	*
S_4	Switch, Part of Ass'y A_2	11837	*	1	*
S_5	Switch, Part of Ass'y A_2	11837	*	1	*
S_6	Switch, Part of Ass'y A_3	11837	*	1	*
	MISCELLANEOUS				
	Dial, DQ	11837	2780	1	
	Dial, Function	11837	3242	1	
	Dial, Main dial 1st	11837	4275	1	
	Dial, Main dial 2nd	11837	3332	1	
	Dial, Main dial 3rd	11837	3333	1	
	Dial, DQ mult	11837	3346	1	

* Replace entire Ass'y

Ckt Ref	Description	Mfr	ESI Part No.	Qty Used	Recm SP
	Dial, Main dial rheostat	11837	3344	1	
	Dial, Range	11837	3243	1	
	Knob	11837	1255	1	
	Cap, Binding Post Ins.	11837	1170	14	4
	Cap, Binding Post Metal	11837	1172	5	2
	Binding Post	11837	1393	19	
	Mask	11837	3375	1	
	Swing lug	11837	3247	2	
	Insulator, Binding Post,	11837	8823	8	
	Shield, Cover	11837	3331	1	
	Shield, Binding Post	11837	3295	1	
	Cover, Dust	11837	3347	1	

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